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14. ABSTRACT
Pairs of moorings containing acoustic Doppler current profilers (ADCPs) were deployed at each end of the Bosphorus Strait as a part of the United States Naval Research Laboratory's "Exchange Processes in Ocean Straits (EPOS)" project. The moorings were deployed in September 2008 and remained in place for about half a year. For the first time, current velocity profiles were collected concurrently at both ends of the strait. They well resolved the two-layer exchange flow and were used to estimate volume flux time series. These estimates clearly indicated that there was a mean net volume flux of over 100 km^3/yr directed from the Black Sea to the Sea of Marmara over this period. The upper-layer fluxes showed distinct temporal variability whereas the lower-layer fluxes varied less. Volume fluxes were maximized at over 1500 km^3/yr in the upper layer and over 1100 km^3/yr in the lower layer, with an upper-layer mean of about 400 km^3/yr and a lower-layer mean of about 300 km^3/yr. Fluxes in both layers were highly coherent with the bottom pressure difference between the southern and northern ends of Bosphorus Strait, and they can be fairly well predicted from this pressure difference. The fluxes in the upper layer were also influenced by atmospheric forcing, but generally less so than by the bottom pressure difference.

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Observed volume fluxes in the Bosphorus Strait

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[1] Pairs of moorings containing acoustic Doppler current profilers (ADCPs) were deployed at each end of the Bosphorus Strait as a part of the United States Naval Research Laboratory's "Exchange Processes in Ocean Straits (EPOS)" project. The moorings were deployed in September 2008 and remained in place for about half a year. For the first time, current velocity profiles were collected concurrently at both ends of the strait. They well resolved the two-layer exchange flow and were used to estimate volume flux time series. These estimates clearly indicated that there was a mean net volume flux of over 100 km^3/yr directed from the Black Sea to the Sea of Marmara over this period. The upper-layer fluxes showed distinct temporal variability whereas the lower-layer fluxes varied less. Volume fluxes were maximized at over 1500 km^3/yr in the upper layer and over 1100 km^3/yr in the lower layer, with an upper-layer mean of about 400 km^3/yr and a lower-layer mean of about 300 km^3/yr. Fluxes in both layers were highly coherent with the bottom pressure difference between the southern and northern ends of Bosphorus Strait, and they can be fairly well predicted from this pressure difference. The fluxes in the upper layer were also influenced by atmospheric forcing, but generally less so than by the bottom pressure difference. **Citation:** Jarosz, E., W. J. Teague, J. W. Book, and Ş. Beşiktepe (2011), Observed volume fluxes in the Bosphorus Strait, *Geophys. Res. Lett.*, *38*, L21608, doi:10.1029/2011GL049557.

1. Introduction

[2] The narrow and geometrically complex Bosphorus Strait is the only pathway connecting the semi-enclosed Black Sea with the Sea of Marmara, and, through the Dardanelles Strait, with the Aegean and the Mediterranean Seas. Hence, it plays a paramount role in water-mass exchange among these basins. It has been established for decades that the flow in the strait is a two-layer exchange with brackish waters originating in the Black Sea in the upper layer flowing southward and salty waters from the Sea of Marmara moving northward below [*Ünlüata et al.*, 1990; *Özsoy et al.*, 1998; *Gregg and Özsoy*, 2002]. In the Black Sea, the sum of riverine discharge and precipitation is not balanced by evaporation and results in a net outflow of brackish waters through the Bosphorus Strait from the Black Sea. This freshwater surplus was estimated to be somewhere between 200 km^3/yr and 300 km^3/yr [*Ünlüata et al.*, 1990; *Simonov and Altman*, 1991; *Peneva et al.*, 2001; *Kara et al.*, 2008].

[3] Based on long-term averages of the salinity along the northern and southern ends of the strait, and assuming steady-state mass budgets, *Ünlüata et al.* [1990] evaluated mean annual volume transports in the upper and lower layers to be about 612 km^3/yr (1 km^3/yr ~ 31.71 m^3/s) and 312 km^3/yr in the northern Bosphorus and 635 km^3/yr and 336 km^3/yr in the southern Bosphorus, respectively. These values were later updated, for example, by *Beşiktepe et al.* [1994] and *Tuğrul et al.* [2002]. Estimates of volume fluxes calculated from shipboard ADCP current observations collected over years, however, did show great monthly and seasonal variability around the annual means [*Beşiktepe et al.*, 1994; *Özsoy et al.*, 1998; *Altiok et al.*, 2010]. Near the northern (Black Sea) entrance of the strait, fluxes varied between 5 km^3/yr and 1051 km^3/yr in the upper layer and between 0.6 km^3/yr to 866 km^3/yr in the lower layer, while near the southern (Marmara) entrance, fluxes ranged from 0 km^3/yr to1216 km^3/yr in the upper layer and from 0 km^3/yr to 654 km^3/yr in the lower layer as calculated from shipboard ADCP current data collected monthly between 1999 and 2009 [*Altiok et al.*, 2010]. In general, the largest fluxes in both layers are usually observed in spring, whereas the lowest volume transports in the strait are usually recorded in fall [*Tuğrul et al.*, 2002].

[4] The United States Naval Research Laboratory (NRL) and the NATO Undersea Research Center (NURC) in collaboration with the Turkish Navy Office of Navigation, Hydrography and Oceanography deployed two mooring sections in the Bosphorus Strait as a part of the TSS08 (NURC project) and EPOS programs in September 2008 and recovered them earlier than planned at the beginning of February 2009 due to logistics problems (Figure 1). Each mooring section was configured with a bottom-mounted Barny mooring (M5 and M7), one line mooring (TC3 and TC4) in the deep channel, and another Barny mooring (M6 and M8) to the east in a shallower part of the channel. Barny moorings contained an ADCP instrument, a wave/tide gauge, and conductivity sensor. Line moorings were equipped with seven and six temperature and conductivity sensors in the northern and southern sections, respectively. All sensors recorded data at 15-minute intervals. More detailed descriptions of the EPOS and meteorological observations examined here are in the work of *Jarosz et al.* [2011] and auxiliary materials.[1] The deployment delivered nearly full water-column current profiles along both ends of the strait. These observations then provided the first concurrent estimates of the volume transports at both locations (methodology used in flux calculations is described in auxiliary materials).

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL049557.

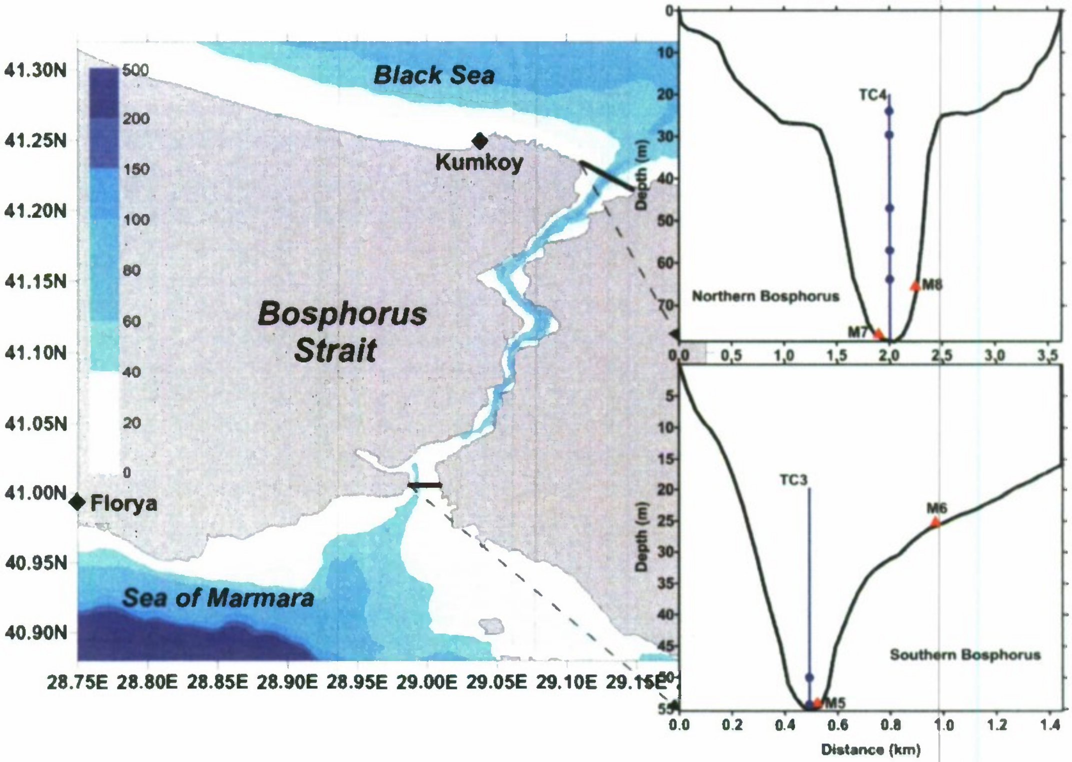

Figure 1. Map of the Bosphorus Strait and cross-sections used in flux estimations; color scale – depths in meters; red triangles – Barny moorings (M5, M6, M7, and M8); blue line – line moorings (TC3 and TC4); blue dots – conductivity and temperature sensors that were recovered and returned high-quality data. Meteorological stations, Florya and Kumköy, are also shown.

Time variability of these volume fluxes and possible forcing of the flux fluctuations are discussed in this paper.

2. Volume Fluxes

[5] Figure 2 displays time series of the volume fluxes for both layers and the net transport along the northern and southern sections in the Bosphorus Strait. Means of each time series are also shown in Figure 2. Positive numbers represent a flux towards the Black Sea, whereas negative values represent a volume transport towards the Sea of Marmara. The temporal variability of all fluxes was evident, and it was more pronounced for the upper-layer fluxes than for the lower-layer fluxes along both sections (Figure 2 and Table 1). Fluctuations at the same layer were very similar in amplitudes and directions. Hence, it is not unexpected for coherence squared to be high between the sections and to be between 0.6 and 0.95 for the upper layer, between 0.5 and 0.93 for the lower layer, and between 0.87 and 0.98 for the net fluxes for various frequencies (coherence squared higher than 0.19 is significant here, i.e., it is statistically considered to be different from 0). Fluctuations were often two to three times larger than the record means. Additionally, fluxes in the upper layer completely reversed a number of times. Those events were usually caused by storms passing over the region such as one at the beginning of October 2008 and another around November 20, 2008. The influx of the salty waters to the Bosphorus Strait was observed continuously in the southern strait; however, on several occasions, the lower-layer flux in the northern Bosphorus to the Black Sea was significantly reduced, blocked, and even reversed for a day or two, which was especially evident in a sequence of events observed between December 20, 2008 and January 15, 2009.

[6] Table 1 presents mean volume fluxes, flux range, and root-mean-square errors (rms). The upper-layer flux had a mean of -375 km^3/yr in the northern Bosphorus and a mean of -444 km^3/yr in the southern Bosphorus. The lower-layer flux had means of 253 km^3/yr and 333 km^3/yr in the northern and southern Bosphorus, respectively. The means for both layers exceed those estimated from the mass budget for the corresponding year period by at least 50% [*Tuğrul et al.*, 2002]; they are, however, comparable to mean values estimated from the shipboard ADCP observations [*Altiok et al.*, 2010].The net flux varied significantly throughout the deployment (Figure 2 and Table 1) and its means, which are -122 km^3/yr and -111 km^3/yr for the northern and southern sections, respectively, indicate that there were net outflows towards the Sea of Marmara through both sections.

[7] The errors given in Table 1 represent the level of statistical uncertainty for assigning perfectly accurate mean fluxes for our deployment period. They do not directly include errors associated with measurement errors and insufficient sampling that led to spatial interpolation and extrapolation of the current velocities in each mooring section. An average measurement error for our ADCPs was about ± 1.94 cm/s (random + bias errors). This error led to an average uncertainty in flux estimations of about ± 13 km^3/yr in both sections. It is impossible to perfectly evaluate an

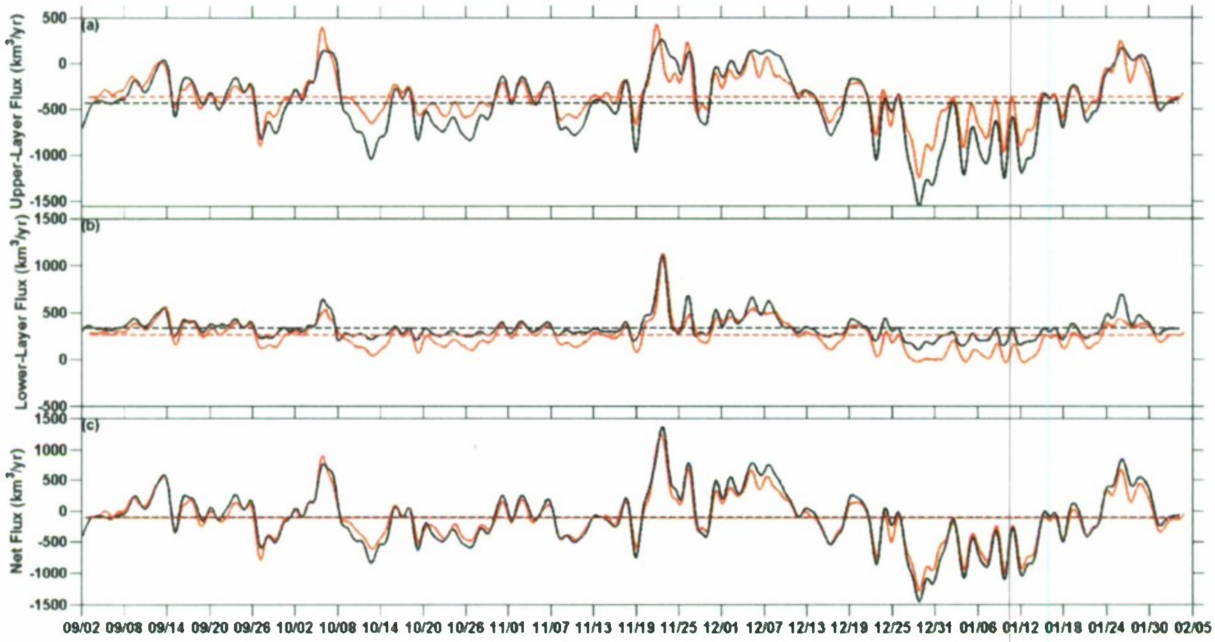

Figure 2. (a) Upper-layer, (b) lower-layer, and (c) net volume fluxes (continuous lines) and their means (dashed lines) in the northern (red lines) and southern (black lines) Bosphorus Strait (positive values – flux towards the Black Sea; negative values – flux towards the Sea of Marmara).

error associated with undersampling and ensuing interpolation of the current observations; thus, we estimated volume transports using observations just from one mooring in each section (M5 and M7) to understand how even less data may impact our results. The calculations showed that a flux error for both locations was, on average, 10 km^3/yr. Comparing these errors to the errors in Table 1 and the flux differences from different techniques in extrapolating currents to the surface (auxiliary materials) shows that measurement errors and horizontal interpolation/extrapolation errors are not likely to be the dominate errors in our estimation of the flux means.

3. Forcings

[8] Time series of the wind stress, atmospheric pressure, and the bottom pressure difference (BPD) between southern and northern sections estimated from the bottom pressure measurements after removing record means are shown in auxiliary materials and discussed in more detail by *Jarosz et al.* [2011]. All these variables are considered to be possible driving mechanisms of the flux fluctuations in the Bosphorus Strait, and some correlations between them and volume transports are visually apparent. Strong winds were responsible for blockages and/or reversals of the upper-layer fluxes, while negative values of the BPD were able to significantly reduce and even reverse the lower-layer flux along the northern Bosphorus.

[9] To quantify visual comparisons of the concurrent time series of the atmospheric forcing, the BPD, and volume fluxes of the upper layer, and to evaluate relationships among them, multiple and partial coherences were used. Results from this analysis are displayed in Figures 3a and 3b. In the northern section, the multiple coherence results indicate that the atmospheric forcing and the BPD accounted for about 80% of the flux variance for frequencies less than 0.6 cpd (Figure 3a). The same driving mechanisms could explain 69% or more of the upper-layer flux fluctuations along the southern section (Figure 3b). Partial coherence results show that the primary forcing of these variations was the BPD between the southern and northern sections. Its impact on the fluxes in the upper layer was very pronounced. Atmospheric forcing also impacted the flux fluctuations; however, its importance was clearly secondary compared to the BPD. Additionally, atmospheric forcing was more effective as a forcing in the northern Bosphorus than in the southern Bosphorus, especially the wind stress. In the southern Bosphorus, only the along-strait wind stress among the atmospheric variables had partial coherence squared rising above the statistical significance level.

[10] Simultaneously, fluctuations observed in the volume fluxes of the lower layer were very coherent with the BPD

Table 1. Mean Volume Fluxes (km^3/yr), Their Estimated Root-Mean-Square Errors (km^3/yr) and Range (min/max)[a]

Sections	Northern Bosphorus	Southern Bosphorus
Upper layer		
Mean	−375	−444
Error	75	108
Range	−1249/422	−1554/248
Lower layer		
Mean	253	333
Error	50	25
Range	−41/1129	−98/1104
Net flux		
Mean	−122	−111
Error	83	98
Range	−1276/1220	−1453/1352

[a]Positive numbers represent a flux towards the Black Sea, negative values represent a volume transport towards the Sea of Marmara.

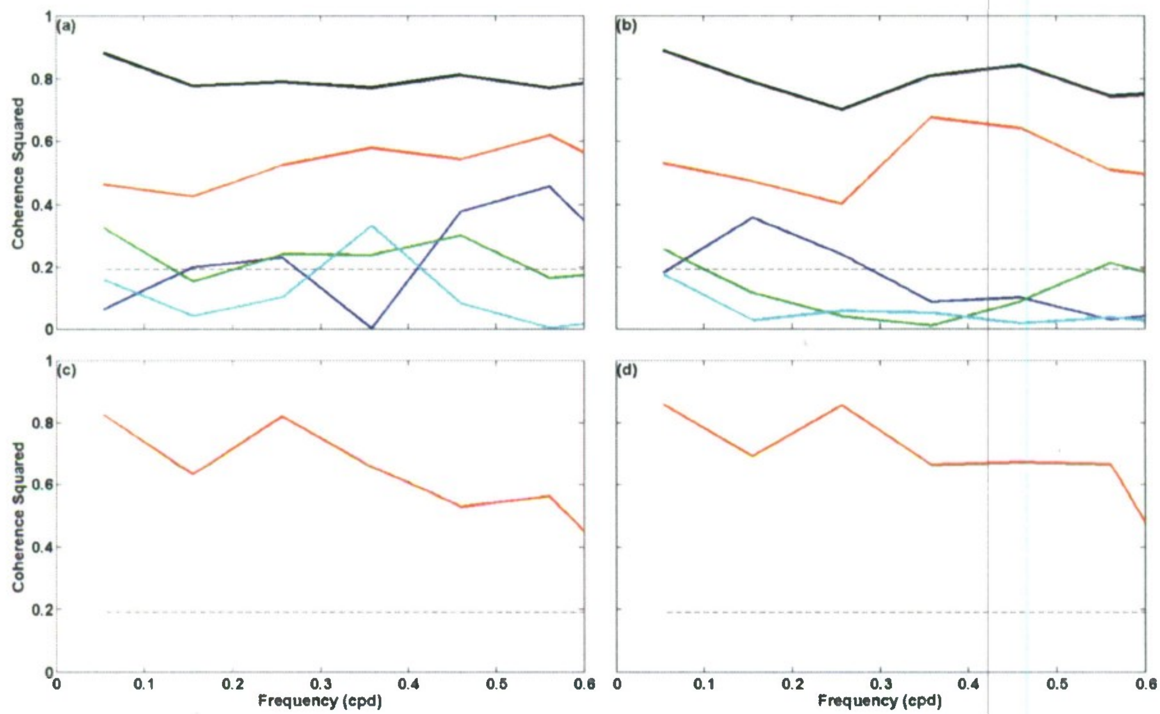

Figure 3. Multiple (black line) and partial (color lines) coherence between the fluxes of the upper layer in the (a) northern and (b) southern Bosphorus Strait and the bottom pressure difference (red line), the along- (blue line) and across-strait (green line) wind stresses, and the atmospheric pressure (cyan line). Coherence squared between the fluxes of the lower layer in the (c) northern and (d) southern Bosphorus Strait and the bottom pressure difference. The atmospheric pressure and the winds from Kumköy and Florya were used to estimate the wind stress for the coherence analyses for the northern and southern sections, respectively. Frequencies are in cycles per day (cpd).

(Figures 3c and 3d). In the northern Bosphorus, this forcing accounted for on average 67% of the flux variance, whereas it explained about 73% of the flux variability in the southern part of the strait. Note, however, that the simple coherence squared between the lower-layer fluxes and the BPD could also include an indirect impact of the atmospheric forcing on these fluxes because this particular statistical approach does not exclude a possible direct influence of the winds and the atmospheric pressure on the observed BPD.

[11] To further clarify the role of the BPD and local atmospheric forcing as major forces controlling flux variability in the Bosphorus Strait, a multiple linear regression model was used. A visual comparison of the currents/fluxes and forcing mechanisms indicate that a response of the flux to changing atmospheric forcing and the BPD usually lagged the evolving forcings. Thus, before calculations of the regression coefficients the cross-correlation between fluxes and forcing variables was used to find lag times (Δt) among them. These lag times were used to shift forcing variables (if required) and then the regression coefficients were calculated. Results for the volume transports in the southern Bosphorus are shown in Figure 4. The agreement between fluxes estimated from the current observations and calculated from the regression equations is rather remarkable considering the complexity of the exchange dynamics in this strait and our simplistic approach. In the upper layer, a rough flux estimate may be calculated from known observations of the BPD and atmospheric forcing (Figure 4a; correlation squared (R^2) = 0.8; $\mathrm{Flux}(t) = 0.213\mathrm{BPD}(t-5) + 6613.4\tau_u(t-12) + 7157.9\tau_v(t-12) - 8.8195p_{atm}(t-10) + 8555.4$ where t is the time) or from the BPD alone (Figure 4a; $R^2 = 0.73$; $\mathrm{Flux}(t) = 0.2538\mathrm{BPD}(t-5) - 444.4158$). Δt for these calculations were 12, 10, and 5 hours for the wind stress components (τ_u, τ_v), the atmospheric pressure (p_{atm}), and the BPD, respectively. The lower-layer flux is also well-estimated just from the BPD observations (Figure 4b, $\Delta t = 0$, $R^2 = 0.77$, $\mathrm{Flux}(t) = 0.0914\mathrm{BPD}(t) + 332.7196$). Note that the forcing mechanisms are correlated; thus, the fluxes estimated just from the BPD also include an indirect input from the atmospheric forcing because this statistical approach does not exclude a direct influence of the winds and the atmospheric pressure on the observed BPD. Similar results from the multiple regression analysis were also obtained for the volume transports in the northern Bosphorus, for instance, the same regression equations for the upper-layer transport are $\mathrm{Flux}(t) = 0.1294\mathrm{BPD}(t) + 352.2138\tau_u(t-3) + 3566.6\tau_v(t-9) - 6.5636p_{atm}(t-3) + 6303.6$ ($R^2 = 0.76$) and $\mathrm{Flux}(t) = 0.174\mathrm{BPD}(t) - 375.5152$ ($R^2 = 0.7$). A regression line for the lower-layer flux is $\mathrm{Flux}(t) = 0.1131\mathrm{BPD}(t-4) + 252.2446$ ($R^2 = 0.77$). Considering how logistically difficult and expensive instrument deployments are to collect current observations such an approach could be a viable option for flux estimations and monitoring in the Bosphorus Strait.

4. Entrainment and Mixing

[12] Historical observations of salinity and those collected for the EPOS project indicate that the upper-layer waters

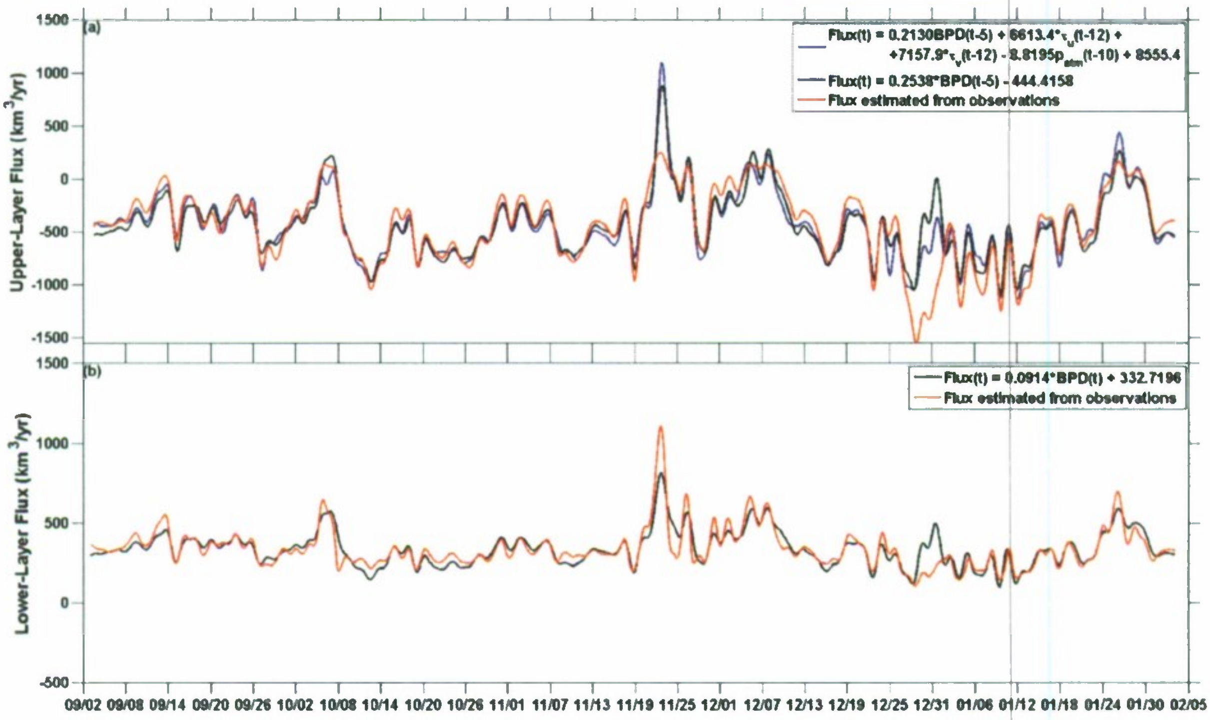

Figure 4. Results from regression models for (a) upper- and (b) lower-layer fluxes in the southern Bosphorus Strait; BPD is the bottom pressure difference, τ_u is the along-strait wind stress, τ_v is the across-strait wind stress, p_{atm} is the atmospheric pressure; meteorological observations are from Florya.

become more saline while the lower-layer waters become fresher when traversing the strait. The EPOS salinity and current data allowed calculations of fluxes of high salinity waters (37 psu and higher). Record-long averages were 180 km^3/yr (rms = 12 km^3/yr) and 37 km^3/yr (rms = 17 km^3/yr) in the southern and northern sections, respectively. The difference between these means is 143 km^3/yr (rms = 8 km^3/yr) and implies that on average, this amount of the high salinity water was mixed in or/and entrained from the lower layer to the upper layer in the strait.

[13] The time series of the high-salinity flux differences (Q) was further used to estimate a strait-averaged entrainment velocity and eddy diffusivity (Figure 5). For these computations, it was assumed that the average width and length of the Bosphorus Strait are 1.5 km and 30 km, respectively. The entrainment velocity was found from the following: u_{ent} = Q/Area and, on average, it was 10^{-4} m/s (Figure 5c). Following *Kullenberg* [1977], the vertical flux can be expressed as $u_{ent}\Delta\rho = -K_\rho(d\rho/dz)$ where K_ρ is the eddy diffusivity, ρ is the density, and $\Delta\rho$ is the density difference between the upper and lower layers. This expression led to the eddy diffusivity (48-hour averages) shown in Figure 5d. The layer-averaged densities estimated from our observations were used in these computations. K_ρ was consistently on the order of 10^{-3} m^2/s, indicating strong mixing. It also showed some variability over time with the higher values generally associated with strong winds. It should be also noted that mixing is not spatially uniform in the Bosphorus Strait as discussed by *Gregg and Özsoy* [2002]; hence, eddy diffusivity also varies and it can be much higher or lower than our estimates in some parts of this strait. The high values of K_ρ in the Bosphorus Strait were confirmed by microstructure observations collected near M7 in September 2008. Energy dissipation rates estimated from microstructure shear observations indicate that K_ρ varied with depth and was as high as 10^{-2} m^2/s there.

5. Summary

[14] The current observations collected at both ends of the Bosphorus Strait by the ADCP-equipped moorings allowed estimations of volume fluxes for a period of time between September 2008 and February 2009. These estimates clearly indicated that there was a net volume flux directed from the Black Sea to the Sea of Marmara. The upper-layer fluxes showed distinct temporal variability along both northern and southern sections. Observed fluctuations were often two to three times larger than computed record means. In the lower layer, the volume transport also displayed some variability; however, this variability was less pronounced than that of the upper-layer fluxes. Flux fluctuations in both layers were highly coherent with fluctuations of the BPD between the southern and northern Bosphorus Strait. Such a well-defined relationship indicates that this difference was a major driving forcing of the volume transport fluctuations during the observational period. As a result, the fluxes in both layers could be fairly well-predicted from this pressure difference. Additionally, the fluxes in the upper layer were impacted by atmospheric forcing, but more in the northern Bosphorus than in the southern Bosphorus. The data also indicate that there was strong mixing in this strait with the eddy diffusivity being consistently on the order of 10^{-3} m^2/s.

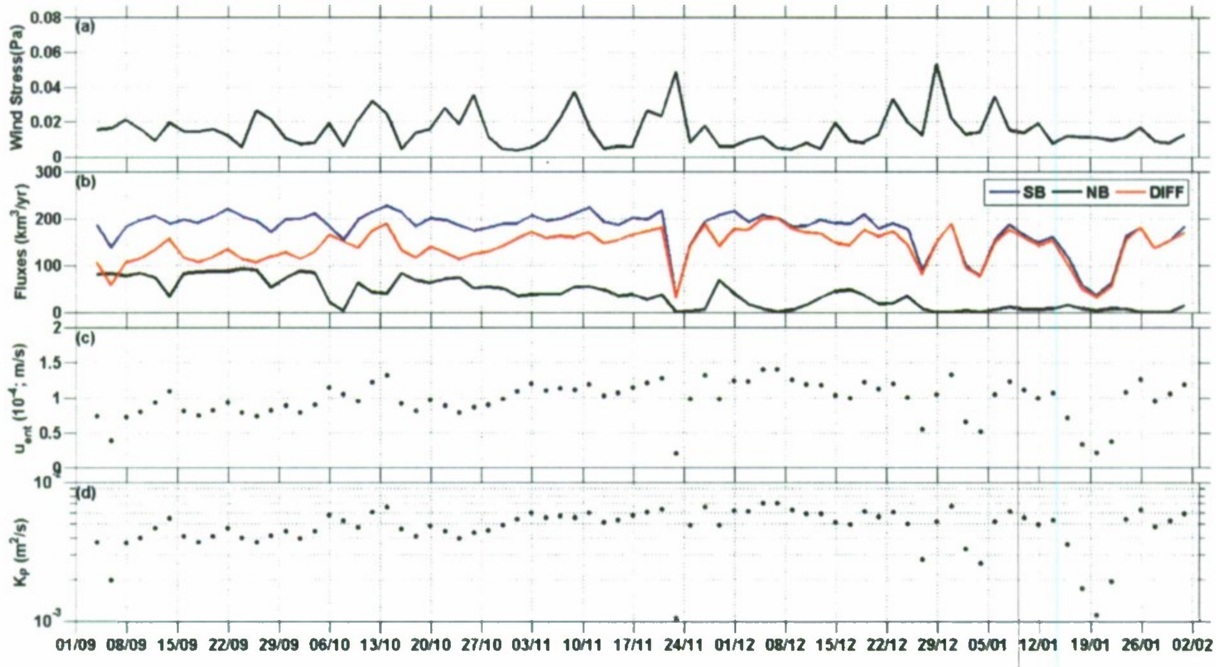

Figure 5. (a) Wind stress magnitude (Pa) from Florya; (b) volume fluxes (km^3/yr) of waters with salinity 37 psu and higher (blue – southern Bosphorus, black – northern Bosphorus, and red – a flux difference between the southern and northern Bosphorus); (c) entrainment velocity (m/s); (d) eddy diffusivity (m^2/s).

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